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Plant diversity assessment of karst limestone, a case study of Malaysia's Batu Caves

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Abstract
Batu Caves hill is typical of karst hills in Peninsular Malaysia due to its small size and high biodiversity. It harbours 366 vascular plant species that represent about 25% of the Peninsula's limestone flora. Five species are endemic to Batu Caves and 23 are threatened species. This high biodiversity is the result of many microhabitats, each with their own assemblages of species. Threats are especially severe as the area of Batu Caves is surrounded by urbanisation that encroaches to the foot of cliffs, is vulnerable to fire, habitat disturbance and, formerly, by quarrying. Assigning a Conservation Importance Score (CIS) to all species is quantitative and accurate, can be implemented rapidly and produces reproducible results. Species with highest CIS are native species of primary vegetation, restricted to limestone substrates, endangered conservation status and, in this case, endemic to Batu Caves. It allows not only species, but microhabitats, sites within a hill and different hills to be compared. By identifying and surveying all microhabitats and focusing on locating endemic and threatened species, maximum biodiversity can be captured. Of the 16 microhabitats identified, the most threatened were the buffer zone, lower levels of steep earth-covered slopes and cave entrances. Application of this method provides a scientific basis for balancing the need to protect microhabitats and sites with the highest CIS, with their multiple uses by various stakeholders, which, at Batu Caves, include the activities of cave temples and eco-recreation. It also provides a scientific quantitative method to compare hills to ensure that those hills with highest CIS are not released for mining.

Keywords
Conservation Importance Score, Important Plant Areas, microhabitats, quarrying, threatened species

Introduction

Karst limestone hills throughout SE Asia are under severe threat as the demand for cement and other limestone products (Clements et al. 2006) frequently takes precedence over conservation of biodiversity, eco-tourism, recreation, culture (cave temples) and their iconic landscape value (Kiew 1997). Peninsular Malaysia is no exception and it is common to see karst hills scarred by quarry faces of active or disused quarries. In Peninsular Malaysia, of the 445 limestone hills, 73 have been quarried or are currently being quarried (Liew et al. 2016). Destruction by quarrying is permanent and irreversible.

Limestone vegetation is distinct from the surrounding lowland forest, not only in its species composition, but also in its appearance (Saw 2010). Its flora is extremely diverse in comparison with the small area it occupies. In Peninsular Malaysia, 14% of vascular plant species (1,216 species) occur on limestone hills and islands that occupy 0.2% of total land area (Chin 1977). High biodiversity is the result of the many and varied microhabitats, the product of the fine scale topographic heterogeneity of karst hills, stacked on a single karst hill (Kiew 1991). Endemic species, especially those with narrow distributions (Kiew et al. 2017) and species restricted to growing on limestone are characteristic of the flora and these are the ones particularly vulnerable to extinction resulting from habitat disturbance and other threats. It is not generally appreciated that plant species are not distributed uniformly over a karst hill, but, on the contrary, the great majority are narrowly distributed in specific microhabitats. This misconception led Vermeulen and Whitten (1999) to suggest that, if part of a karst were retained, the rest could be quarried without significant loss of biodiversity. This is clearly not the case and would, if followed, have devastating consequences for plant diversity.

Although most karst hills in Peninsular Malaysia are small with a basal area of about 1 km^2 or less (Liew et al. 2016), their rugged topography supports many diverse microhabitats, each with a different assemblage of species. These microhabitats (Table 1) have been described by Chin (1977, pp. 177–182) and Kiew (1997). Zhang et al. (2013) have similarly identified at least six different microhabitats in karst hills in SW China.

In Peninsular Malaysia, karst limestone hills are recognised nationally as Environmentally Sensitive Areas and, nowadays, it is a mandatory legislative requirement to carry out an Environmental Impact Assessment (EIA) before quarrying can proceed (Briffett et al. 2004). While EIAs should assess the impact of quarrying on biodiversity, in practice, the data are often deficient because of inappropriate methodology. By using traditional methods of generating species lists from transects and quadrats, the EIAs capture neither the total biodiversity nor the rare endemic species; due to the impracticability of setting quadrats and 100 m long transects on rugged and uneven terrain, they are usually sited on flat land around the base of the karst. However, a single transect will not cover even a fraction of the diversity of microhabitats, particularly those that are inaccessible, such as the vertical cliffs or stalactites or the craggy summit. In addition, often no attempt is made to re-find rare, endemic and/or threatened species that are already known from the site that occupy specific, narrowly restricted

microhabitats (Kiew et al. 2017). Therefore, a novel approach is called for that will address these deficiencies and ensure that maximum biodiversity is captured by targeting all microhabitats and focusing on rare, endemic and threatened species.

In common with much of SE Asia, the greatest impediment to conservation management of karst limestone hills is the knowledge gap, particularly for distribution of species. In many areas, the flora is still incompletely known and it is common for new species, especially of rare species with restricted distribution, to be discovered. To close the knowledge gap, it is necessary to identify and survey all the microhabitats. Sampling microhabitats is more common for invertebrates (Mehrabi et al. 2014) and has rarely been carried out for limestone plants, but notable exceptions are the tree survey by Zhang et al. (2013) in SW China and of dolines in Hungary (Batori et al. 2019). Once species and their microhabitats have been surveyed, species, their microhabitats and sites can be scored for their conservation importance. Thus, Batu Caves can serve as a case study for a methodology of assessing biodiversity that can be applied to and enable comparison between the other 445 limestone karsts in Peninsular Malaysia and for karst hills in the region and can serve as a basis for designating Important Plant Areas (IPAs).

In addition, because of stakeholders' interest in the exploitation or use of the karsts, not only by mining companies, but also by resorts, temples, eco-tourism and local farmers etc., it is necessary to demonstrate which parts of the karst hill harbour the highest biodiversity, so that adjustments for exploitation can balance stakeholder interests with safeguarding critical microhabitats in order to protect maximum biodiversity. A quantitative method is therefore required that will reflect the conservation importance, not only of species, but also of microhabitats with the highest biodiversity. The Batu Caves survey was the first step to obtain comprehensive data for formulating a management strategy on safeguarding the future of this iconic karst and, because Batu Caves had been quarried in the past, it also enables assessment of what biodiversity is left and is worth conserving after a karst hill has been quarried and to investigate whether the indigenous flora is able to re-colonise these disused quarries.

Implementing Conservation Importance Scores (CIS) is a novel quantitative methodology that combines a detailed survey that identifies and surveys all microhabitats and focuses on re-finding key species (site endemics and threatened species).

CIS incorporates criteria such as geographic distribution, vegetation type and conservation status, so that the impact of quarrying and other threats on the long-term survival of species can be determined. To achieve this, it is necessary to identify: (i) species of conservation importance, (ii) the microhabitats where they grow and (iii) sites which have the highest total CIS. Assigning conservation values has been successfully applied for comparing the relative conservation values, for example, at the locality level in comparing different estuaries in Australia (Turpie et al. 2002) and between landscapes in Africa (Lynam et al. 2004). However, karst limestone hills present a very different scenario where plant species are very unevenly distributed due to the rugged topography that produces many microhabitats, each with their different assemblages of species. In addition, in Malaysia endemism is high and many species are confined to a

single or very few karst hills (Kiew et al. 2017). Hence a novel methodology is required to capture and evaluate this diversity and is of conservation importance.

Using Batu Caves hill as a case study, we aim to develop:

(i) a methodology for comprehensively sampling plant diversity on karst limestone hills by surveying all microhabitats that each have distinct assemblages of species and;

(ii) appropriate criteria for scoring species, microhabitats and hills for their conservation importance. For example, compared with other studies, level of endemism and whether species are restricted to limestone substrate are particularly important in evaluating conservation value.

Applying this methodology will close the knowledge gap and has potential to be upscaled to the national level by providing comprehensive and quantitative data for comparing the relative conservation importance of different limestone hills so that limestone hills with outstanding biodiversity can be identified and prioritised for permanent legal protection. In addition, sampling microhabitats identifies where species of conservation importance are found, which will enable decision-making and planning for commercial uses of a hill to ensure minimum intervention of critical microhabitats and sites that would endanger rare endemic species.

Materials and methods

Study Site (Figure 1)

Batu Caves, Selangor (called *Gua Batu* or *Bukit Batu* in Malay) is an iconic tower karst limestone hill that dominates the landscape. It lies about 12 km northeast of Kuala Lumpur, the capital city of Malaysia. It covers about 1.1 km^2 and reaches 329 m at the highest point. It lies 3° north of the Equator. Day length varies just 15 min between June and December. The climate is equatorial with annual temperature variation much smaller than the diurnal variation with highest day and night temperatures of 33 °C and 23 °C, respectively, in April and the lowest temperatures of 31 °C and 22 °C in January. Mean annual rainfall is 2540 mm. June is the driest month with 130 mm of rain in 13 rainy days while November is the wettest month with 24 rainy days and 278 mm of rain. Humidity averages about 80% throughout the year. The karst is covered in limestone forest (Saw 2010).

Batu Caves is not only an outstanding nature monument, known for its unique plant and animal biodiversity and its caves and cave ecosystem, but it is also a site of great cultural and tourist importance. Its majestic Temple Cave houses the Sri Subramaniarswamy Temple that, during the Thaipusam Festival, attracts more than a million devotees and tourists. Formerly, Batu Caves was surrounded by lowland rain forest, but already by the 1890s, when the first scientific study was conducted (Ridley 1898), coffee plantations were beginning to encroach the area. Due to its accessibility

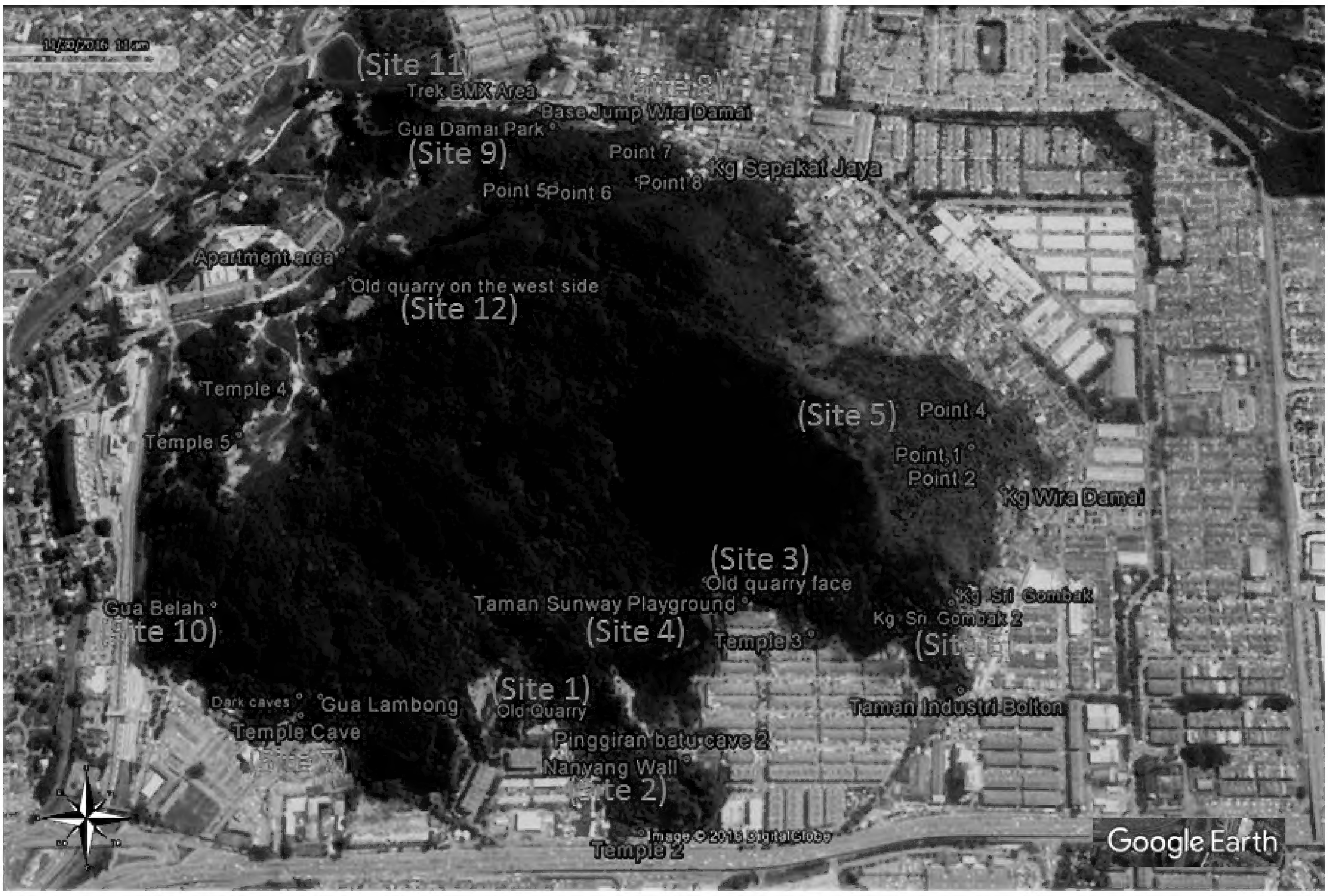

Figure 1. Study sites on Batu Caves, a limestone karst in Selangor, Peninsular Malaysia (Google Maps).

to Kuala Lumpur, over the following 120 years, it has been studied by many scientists with different specialities, making Batu Caves the best studied limestone karst in Malaysia and SE Asia (Kiew 2014; Kiew et al. in press). Batu Caves is home to at least 366 plant species (6 lycophytes, 40 ferns, 2 gymnosperms and 318 flowering plant species) representing 30% of Peninsular Malaysia's limestone flora (Kiew et al. in press).

In 1930, Batu Caves was gazetted as a Public Recreation Area. In the same year, the Sri Subramaniarswamy Temple was placed under the management of the Sri Maha Mariamman Temple. In 2007, the temple complex was designated as a Cultural Heritage Site. In 2016, the entire Batu Caves environmental complex was classified as an Environmentally Sensitive Area. Quarrying on a small scale had already started in 1889. In 1952 and 1959, parts of the Reserve were revoked and quarry licences issued. A third quarry opened in 1972 (Yussof 1997). Quarrying ceased in 1981, but no attempt has been made to rehabilitate the quarry sites and even after 40 years, the cliff faces remain bare and scar the hill. One cave was completely destroyed by quarrying (Lim et al. 2010). The surrounding lowland forest has been progressively cleared and today, there is no longer a buffer zone of trees around the base of the karst. In only a few places does a narrow strip of forest persist. Current major threats include continuing illegal encroachment, increasingly frequent accidental fires and unregulated infrastructure development (Kiew et al. 2019).

In view of these on-going threats, there is an urgent and pressing need to re-evaluate the current status of Batu Caves, particularly its sensitive biodiversity, to assess the

impacts of the various threats and uses. In common with all karst sites, Batu Caves is of finite size, so it is imperative to ensure that any change does not impact negatively and cause permanent loss or damage, while, at the same time, enabling Batu Caves to remain accessible to devotees, tourists, scientists, speleologists and rock climbers etc.

Conservation Importance Score

To identify species of greatest conservation concern, a novel quantitative method, the CIS, was used, based on weighting a combination of parameters (whether the species is a native species, is from primary vegetation, is restricted to limestone, is endemic and its conservation status, based on IUCN Criteria and Categories). For a karst hill, this enables the assessment of species, microhabitats and sites for their conservation importance and identifies species and microhabitats of high conservation value, irrespective of the number of species present.

Initially, the Conservation Importance Scoring system was trialled in 2016 during the Rapid Biodiversity Assessment of Batu Caves and proved rapid and effective in producing accurate, quantitative reproducible results that identified species, microhabitats and sites with maximum biodiversity. It was not only effective at the species, microhabitats and site levels, but also has potential as a robust methodology that enables comparison between limestone karsts on a scientific basis.

For the CIS to be successfully applied, the first step is to identify the many microhabitats found on a single karst hill. By identifying and surveying all microhabitats, those with unique assemblages of species, particularly of threatened species, can be pinpointed. In this way, most of the rare and threatened species will be captured and, by using CIS, those species and microhabitats most at risk can be identified.

Field survey

To evaluate the current status of plant diversity on Batu Caves, a Rapid Biodiversity Assessment was initiated in November–December 2016 and carried on throughout the Batu Caves Scientific Expedition between July 2018 and June 2020. The survey covered the entire base of the karst, the steep earth-covered slopes, areas around caves and the summit where it was accessible without climbing equipment (Table 3). Sixteen microhabitats (Table 1) were identified, each characterised by physical factors (topography, substrate, whether they were exposed or shaded) and their particular assemblage of species. Level of disturbance was also recorded.

All microhabitats at twelve sites were surveyed (Table 3, Suppl. material 1: Appendix). Some sites investigated covered a range of microhabitats. Disturbed, as well as undisturbed sites, were included. Three disused quarry sites were also surveyed. All sites were photographed and geographical co-ordinates were recorded using a Garmin Global Positioning System (GPS). Names of the sites/caves follow those of Lim et al. (2010).

Wherever practicable, transects of variable length (their length depending on the terrain), were set up, either along the base of the hill or vertically up steep earth-

Table 1. Microhabitats on Batu Caves: physical characteristics and level of disturbance.

Microhabitat	Topography	Substrate	Vegetation	Exposure	Disturbance
a	flat base often below overhang of vertical cliffs	bare dry soil	sparse herbs	fully exposed	undisturbed
b	vertical cliff face	bare rock	lithophytes	fully exposed	undisturbed
c	flat base	soil	forest	shaded	undisturbed
d	steep lower slope	deep soil and rocky outcrops	forest	shaded	disturbed
e	steep lower slope	deep soil and rocky outcrops	forest	shaded	undisturbed
f	steep upper slope with	shallow soil and rocky outcrops	forest	shaded	undisturbed
g	hanging valley	wet soil	forest	shaded	undisturbed
h	steep upper slope	shallow soil and rocky outcrops	forest	shaded	disturbed
i	vertical cliff face	no soil, frequently wet	herbs and ferns	shaded	undisturbed
j	scree associated with caves	jumble fallen boulders	forest	shaded	undisturbed
k	cave mouth and stalagmites	frequently damp from percolating rainwater	herbs and ferns	shaded	undisturbed
l	cave interior	dry, guano-rich soil	herbs and ferns	shaded	undisturbed
m	lower summit	dry, peaty soil and outcropping rocks	forest	light shade	undisturbed
n	upper summit	dry, rocky, thin or no soil	forest	light shade	undisturbed
o	flat base	small-sized rubble	weeds or secondary forest	light shaded	disused quarry
p	vertical cliff face	bare rock	none	fully exposed	disused quarry

Table 2. Types of microhabitats on Batu Caves, their extent and level of threat.

	Microhabitat	Extent	No. of sites	Level of Threat
a	Flat base below vertical cliff face	N	2	Vulnerable to encroachment
b	Exposed vertical cliff face	E		Inaccessible to disturbance
c	Flat base with forest	Formally E		Almost eliminated by encroachment
d	Steep lower slope (disturbed by encroachment)	N	4	Disturbed by encroachment
e	Steep lower slope (almost eliminated by encroachment)	N	1	Almost eliminated by encroachment
f	Steep upper slope (undisturbed)	N	2	Vulnerable to encroachment and fire
g	Doline	N	2	Inaccessible to disturbance
h	Steep upper slope	N	2	Disturbance by fire
i	Wet, shaded vertical cliff face	N	3	Vulnerable to disturbance
j	Shaded scree associated with caves	N	3	Vulnerable to disturbance
k	Cave mouth and stalagmites	N	3	Vulnerable to disturbance
l	Cave interior	N	2	Vulnerable to disturbance
m	Lower summit, dry, peaty soil	E		Inaccessible to disturbance
n	Upper summit, dry, rocky, thin or no soil	E		Inaccessible to disturbance
o	Flat base with rubble substrate	N	2	Disturbed by quarrying
p	Vertical cliff face	N	3	Disturbed by quarrying

Extent – E – Extensive (covers a large area); N – Narrow.

covered slopes in gullies as high as was possible to scramble without using climbing equipment or on the summit. Transects were 5 m wide, but of variable length and were often discontinuous depending on the diverse nature of the terrain. All plants along the transect were recorded, microhabitats were identified and the types of threats and level of disturbance recorded. For some microhabitats, for example, vertical cliffs or stalactites, transects were not appropriate, so the entire area was surveyed until no additional species were recorded. Plants on cliff faces were identified visually using binoculars. From the surveys, species lists were generated for each site and for each of their microhabitats (Suppl. material 1: Appendix).

Table 3. Sites surveyed and their microhabitats.

Site/microhabitat*	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p
2. Nanyang Wall	+	+														
4. Taman Sunway playground									+							
3. Taman Sunway car park															+	
5. Kampung Sri Gombak Indah (burned area)								+								
6. Kampung Sri Gombak Indah base				+												
8. Kampung Wira Damai					+	+	+									
11. Trek BMX			+													
7. Temple Cave					+				+	+	+	+				
10. Gua Belah					+	+				+	+	+				
9. Fig Tree Cave Summit													+	+		
1. Disused quarry (south side)															+	+
12. Disused quarry (west side)															+	

*Microhabitat (a-p) – refer to Table 1; In Malay, gua = cave, kampung = village; and taman = park.

For the state of disturbance, sites were assessed visually and by species composition using four categories: more-or-less undisturbed, moderately disturbed, very disturbed and totally disturbed. From a literature search, rare, endemic and threatened species were identified (Kiew 2014) and their habitat gleaned from information on herbarium specimens. These species were specifically searched for and, where found, the current status of their population assessed by counting population size (grouped into: less than 50 individuals, 51–100, 101–250, more than 250) and their life stages (seedling, juvenile and reproductive) were recorded.

Specimen identification

Accurate species identification is of paramount importance, particularly where rare and threatened species are involved. To verify identification and to provide a permanent reference, specimens were collected for each species at first encounter. For Critically Endangered species, only a single shoot was collected to verify its identity without reducing the plant population. Plants with flowers and/or fruits were made into herbarium specimens and deposited in the main collection in the Kepong Herbarium (KEP) at the Forest Research Institute Malaysia. Voucher specimens were made for sterile specimens and stored separately at KEP. Photographs were taken for most species. Identification was based on local floras, recent taxonomic revisions, matching with authenticated specimens in KEP and consultation with specialists.

Evaluating the conservation importance of species, microhabitats and sites

Botanical records

Data were gathered from previous literature on Batu Caves, from herbarium holdings in the Forest Research Institute Malaysia (KEP), University of Malaya (KLU) and

Singapore Botanic Garden (SING). The comprehensive recent botanical inventories from the Rapid Biodiversity Assessment in 2016 and Batu Caves Scientific Expedition in 2019 provided up-to-date information on the vascular plant species still surviving on Batu Caves.

Conservation Importance Scores

To determine the CIS, several criteria were used and scores were assigned (Table 4): provenance (native or alien); whether it is a component of primary or secondary vegetation or is a weed; whether it is restricted to growing on limestone substrates, most frequently grows on limestone or grows on a variety of substrates, i.e. is indifferent to substrate type; and level of endemism, whether it is a site endemic, i.e. known only on Batu Caves or from Batu Caves and a few other sites in the state of Selangor or is endemic in Peninsular Malaysia. Provenance and endemic status were obtained by reference to the species distribution reported in standard floras and Turner (1997) and whether it is restricted to limestone substrates from Chin (1977, 1979, 1983a, b).

Conservation status assessment

Conservation status is important because it indicates the level of threat of extinction of the species. In order to assess the conservation status of Malaysian species, the IUCN Red List Categories and Criteria 3.1 (IUCN 2019) were applied. The IUCN Red List Categories define the extinction risk of the species assessed. A total of nine Red List Categories are used: Extinct (EX), Extinct in the Wild (EW), Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), Least Concern (LC), Data Deficient (DD) and Not Evaluated (NE). Critically Endangered (CR), Endangered (EN) and Vulnerable (VU) species are considered to be threatened with extinction. The conservation status assessment here may be different from those published on the IUCN Red List for plants if a particular taxon is not endemic in Peninsular Malaysia, in which case, it is a regional assessment (Chua and Saw 2006). For species endemic to Peninsular Malaysia, the conservation status is the global status. Extent of Occupancy (EOO) for species restricted to limestone hills is assumed to be same as its Area of Occupancy (AOO) due to substrate restriction. The distributions of all the Batu Caves endangered species fall outside the network of Totally Protected Areas. The comprehensive Taxon Data Information Sheet (TDIS) is used to score each species to produce a relevant conservation status for it in the context of Peninsular Malaysia. The TDIS comprises scientific name, taxonomy details, common names, habitat preferences, geographical range, general distribution pattern, population decline, threats, Red List Categories and Criteria, a rationale for the listing, current conservation measures, utilisation, literature used in assessment, details of assessor(s), date of assessment and names of evaluator.

From the CIS, species, microhabitats and sites could be compared (Table 4). Species of greatest conservation importance are those that score highest (22), the result of a combination of being a native species of primary vegetation, restricted to limestone

Table 4. Criteria for assigning the conservation importance score (CIS) to species, based on scores for provenance, vegetation type, status as a limestone species, endemism and conservation status, based on IUCN Categories.

A. Provenance, vegetation type	Score
Native, primary	4
Native, secondary	2
Native, weed	1
Alien, weed	0
B. Association with limestone substrate	**Score**
restricted	6
usually	4
indifferent	0
C. Endemic	**Score**
Batu Caves	6
Selangor	5
Peninsular Malaysia	4
Not endemic	0
D. Conservation Status	**Score**
CR – Critically Endangered	6
EN – Endangered	5
VU – Vulnerable	4
DD – Data Deficient	3
NT – Near Threatened	2
LC – Least Concern	1
NA – Not Assessed (alien species)	0

Table 5. Number of plant families, genera and species collected in field surveys in 2016–2020 from Batu Caves.

Group/No.	Lycophytes	Ferns	Gymnosperms	Flowering Plants
Species	6	40	2	318
Genus	1	20	1	222
Family	1	14	1	66

habitats, endemic to Batu Caves and Critically Endangered conservation status. Species of no conservation importance with a score of zero are alien weeds that grow on a variety of soil types and have a wide extra-Malaysian distribution and are categorised as Least Concern.

Results

The Batu Caves Flora

The Rapid Biodiversity Assessment survey collected a total 127 plant species in 101 genera and 53 families (Table 5). This is about 34% of the 366 species recorded from Batu Caves since 1890. However, Kiew et al. (in press) document changes in the flora and note that, for example, half the orchid species (20 species) have not been recently collected and that four species, *Polyalthia guabatuensis*, *Sageretia thea* var. *malesiana*,

Sapium insigne and *Sauropus macranthus*, that grew in the buffer zone that has been almost eliminated, are now probably extinct in Malaysia. The crucial factor, however, is whether species of conservation importance persist on Batu Caves and these were the focus of collecting and most were located (Table 6).

1. Species of greatest conservation importance

Species of greatest conservation concern are the threatened species. The Flora of Peninsular Malaysia project is in the process of assessing the conservation status of vascular plants and, to date, about 12% of vascular plant species have been assessed. Of those assessed, 23 species recorded from Batu Caves (Table 6) are provisionally assessed as threatened (Rafidah, in press). Six species were assessed as CR, 13 as EN, three as VU and one as DD. Five species are endemic to Batu Caves and three are endemic in the State of Selangor. A further five species are not endemic, but, in Peninsular Malaysia, are known only from Batu Caves. Threatened species with the highest CIS are the Critically Endangered *Epithema parvibracteatum* and *Rhaphidophora burkilliana*, both endemic in Batu Caves, which score the maximum CIS of 22. Amongst the other threatened species (assessed as Endangered or Vulnerable) are the species restricted to Selangor limestone, *Maxburretia rupicola* and *Ophiorrhiza*

Table 6. Conservation status, vegetation type, microhabitat, endemism and Conservation Importance Score of threatened species.

Species	CS	Vegetation type	Association with limestone	Microhabitat	Endemic	CIS
Epithema parvibracteatum	CR	primary	restricted	j – screes	Batu Caves	22
Impatiens ridleyi	CR	primary	restricted	k – cave mouth	Malaysia	20
Ophiorrhiza fruticosa	CR	primary	restricted	e – lower steep earth-covered slopes	Selangor	21
Psychotria lanceolaria	CR	primary	restricted	f – upper steep earth-covered slopes	Batu Caves	22
Rhaphidophora burkilliana	CR	primary	restricted	j – screes	Batu Caves	22
Schismatoglottis guabatuensis	CR	primary	restricted	g – doline	Batu Caves	22
Calciphilopteris alleniae	EN	primary	restricted	i – shaded, vertical cliff face	Malaysia	19
Argostemma inaequilaterum	EN	primary	usually	e – lower steep earth-covered slopes	Malaysia	17
Beaumontia murtonii	EN	primary	usually	e – lower steep earth-covered slopes	not endemic	13
Begonia phoeniogramma	EN	primary	usually	e – lower steep earth-covered slopes	Selangor	18
Begonia kingiana	EN	primary	restricted	i – shaded, vertical cliff face	not endemic	15
Cnesmone subpeltata	EN	primary	restricted	n – upper rocky summit,	Malaysia	19
Corybas calcicola	EN	primary	restricted	m – lower summit, peaty soil	Malaysia	19
Paraboea paniculata	EN	primary	restricted	b – exposed cliff face	Malaysia	19
Paraboea verticillata	EN	primary	restricted	b, p – exposed cliff face	Malaysia	19
Pararuellia sumatrensis var. *ridleyi*	EN	primary	restricted	m – lower summit, peaty soil	Malaysia	19
Pavetta pauciflora	EN	primary	restricted	e – lower steep earth-covered slopes	Malaysia	19
Piper argyrites	EN	primary	usually	no data	Malaysia	17
Typhonium fultum	EN	primary	restricted	g – doline	Malaysia	19
Jasminum cordatum	VU	primary	restricted	m – lower summit, peaty soil	Malaysia	17
Maxburretia rupicola	VU	primary	restricted	b – exposed cliff face	Selangor	19
Microchirita caliginosa	VU	primary	restricted	i – shaded cliff faces	Malaysia	17
Monophyllaea hirticalyx	VU	primary	restricted	k – cave mouth	Malaysia	17

(M – Malaysia. CS – provisional regional conservation status, CR Critically Endangered, EN Endangered, VU Vulnerable, DD Data Deficient; CIS Conservation Importance Score).

fruticosa that score 19 or 21, respectively, while the nine other threatened species score 13–19 (Table 6). The great majority are restricted to limestone and most are endemic in Peninsular Malaysia.

Table 6 illustrates the wide range of microhabitats (exposed cliff face, lower and upper steep earth-covered slopes, screes, cave mouth, rocky summit, summit with peaty soil, doline and shaded vertical cliffs) in which these threatened species occur and the fact that many are confined to a single specific microhabitat. While some threatened species are common in their microhabitat on Batu Caves, like *Pararuellia sumatrensis* var. *ridleyi* and *Typhonium fultum* and have sizable populations of more than 250 individuals and are represented by all life stages; others are of particular conservation concern due to their small population size. Species that grow on the lower levels of the steep earth-covered slopes are particularly vulnerable to habitat disturbance as is illustrated by the decline in populations of *Argostemma inaequilaterum* and *Begonia phoeniogramma*. The only known population of *Argostemma inaequilaterum* has been eliminated (Chin 1980). We were only able to locate a single specimen of *A. inaequilaterum* in the vicinity of this original population.

The major threat that endangers all these species on Batu Caves is habitat disturbance, whether from encroachment, quarries or fire (Figure 2). The Critically Endangered (CR) species confined to specialised, narrow microhabitats (Table 6) are particularly vulnerable to disturbance. *Epithema parvibracteatum* (Figure 5) and *Rhaphidophora burkilliana* grow only in light shade, wet screes of small, fallen boulders, a microhabitat that is only associated with caves. *Impatiens ridleyi* only grows in light shade on vertical walls of cave mouths or on stalactites that are kept damp by dripping water (Figure 6). In addition, *Epithema parvibracteatum* and *Impatiens ridleyi* are particularly vulnerable, being short-lived herbs that depend on stable conditions to enable the next generation to become re-established from seed. However, the fact that the *I. ridleyi* population has survived at the type site for over a hundred years from its discovery in the 1890s (Ridley 1898) until today in spite of the surrounding anthropogenic activities (Figure 3) indicates that, if a habitat is protected from change, the species can survive indefinitely.

2. Microhabitats of greatest conservation importance

The diversity of microhabitats identified on Batu Caves is illustrated by the 16 microhabitats listed in Tables 1, 2. Characteristic of the limestone flora is the relatively high number of threatened species that occupy specific and often restricted microhabitats (Tables 6, 7). This emphasises that, for any conservation survey of limestone karst hills, a necessary first step is therefore to identify the various microhabitats and their associated species. For the first time, a quantitative method is used that makes it possible to assess the relative conservation importance of each microhabitat, irrespective of the number of species recorded (Suppl. material 1: Appendix). Number of species does not necessarily correlate with the conservation importance of a habitat though this is often used as a criterion in Environmental Impact Assessments (EIA). For example,

Figure 2. Aftermath of extensive accidental burning on Batu Caves.

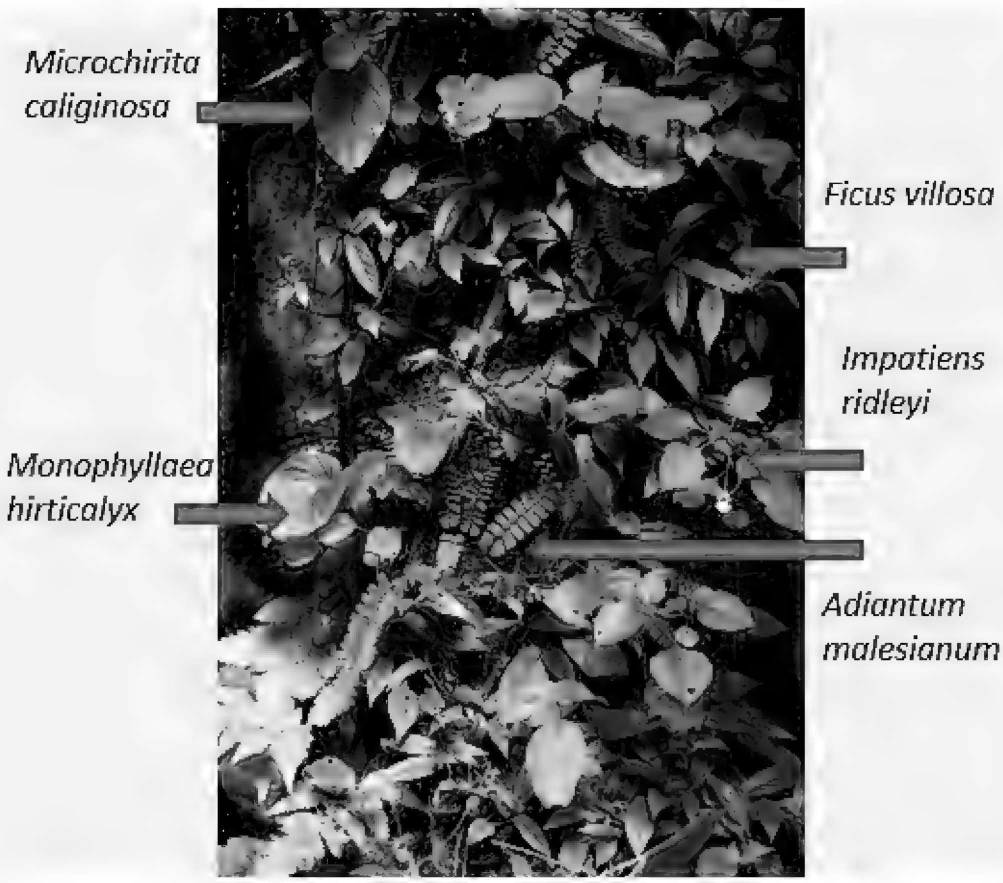

Figure 3. The vertical shaded wall microhabitat illustrates high biodiversity of limestone hills.

the cave mouth at Gua Belah (Site 10) supports 10 species which together have a CIS of 111, compared with the secondary vegetation that grows on the lower slope below Gua Belah and has twice the number of species (21 species), but the CIS is only half (63) that of the cave mouth (Table 8).

Amongst these microhabitats, those that stand out as harbouring most species of conservation importance (Table 7) are the steep, shaded earth-covered slopes (microhabitat f), those associated with caves (microhabitats j and k), the craggy summit (microhabitats m and n), the dolines (microhabitat g) and the vertical wet shaded rock

Table 7. Undisturbed microhabitats at Batu Caves with high conservation importance (based on the total Conservation Importance Score (CIS), presence of threatened, endemic and species restricted to limestone substrates).

	Microhabitats	Site	No. of species	Total CIS	No. of endemic Species	No. of species restricted to limestone	Threatened species
c	Buffer zone	11	16	113	2	6	*Microchirita caliginosa*, *Paraboea verticillata*
f	Steep earth-covered slopes	8.1	79	378	5	4	*Argostemma inaequilaterum*, *Beaumontia murtonii*, *Begonia phoeniogramma*, *Microchirita caliginosa*
		10.2	24	183	4	7	
g	Wet, deeply shaded dolines	8.2	23	174	5	4	*Begonia kingiana*, *Schismatoglottis guabatuensis*, *Typhonium fultum*
i	Wet, shaded vertical cliff face	7.1	20	148	3	5	*Impatiens ridleyi*, *Begonia phoeniogramma*, *Microchirita caliginosa*
j	Shaded scree	10.47.6	30	217	7	4	*Begonia phoeniogramma*, *Epithema parvibracteatum*, *Rhaphidophora burkilliana*
			2	30	1	1	
k	Wet, shaded cave mouth and stalagmites	10.3	10	111	4	6	*Argostemma inaequilaterum*, *Begonia kingiana*, *Impatiens ridleyi*, *Microchirita caliginosa*, *Monophyllaea hirticalyx*
		10.57.2	12	105	3	5	
		7.5	10	58	2	3	
			7	38	1	1	
m & n	summit, dry, peaty soil or dry, rocky	9	25	183	5	7	*Pararuellia sumatrensis* var. *ridleyi*, *Maxburretia rupicola*, *Paraboea verticillata*

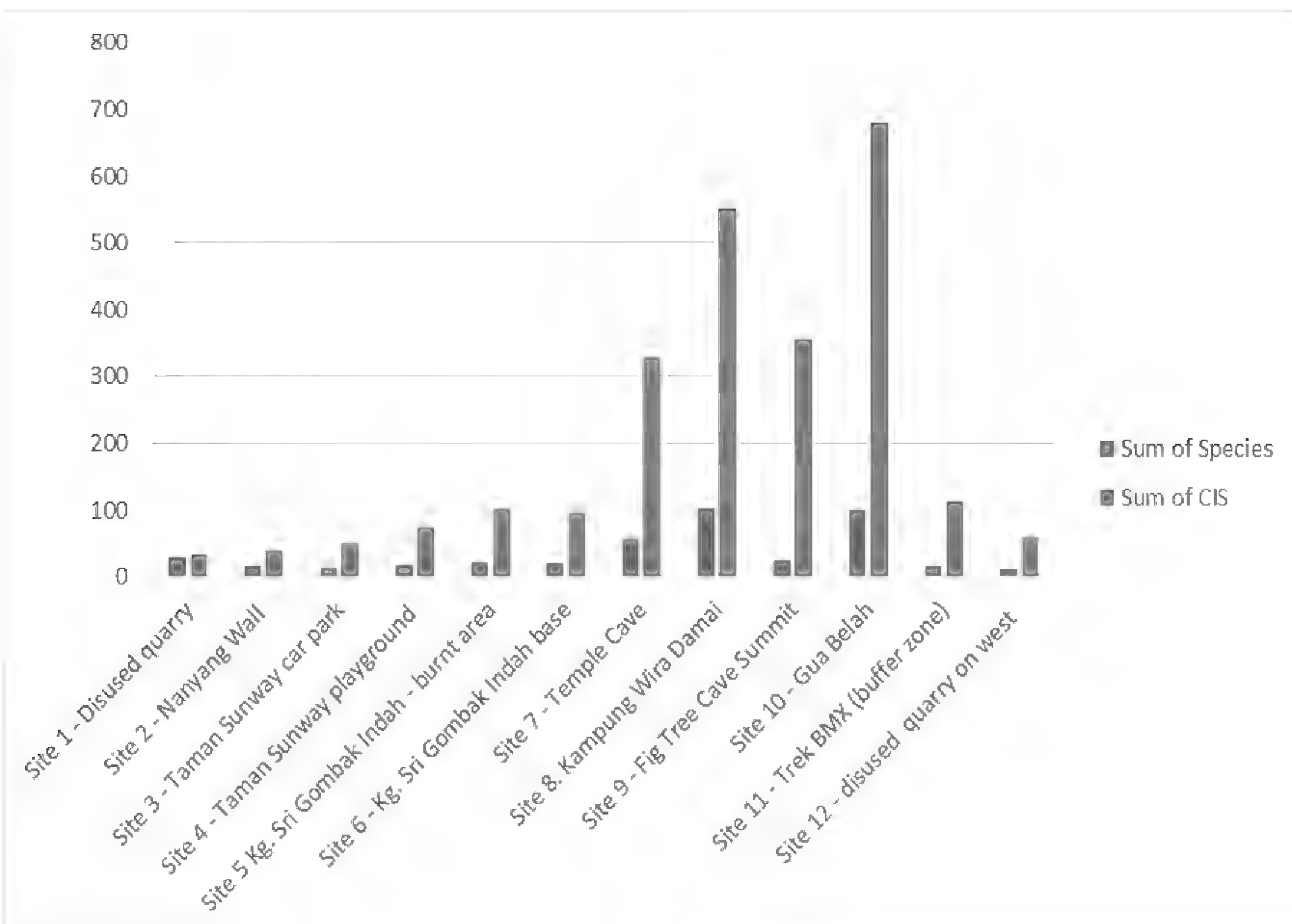

Figure 4. Conservation Importance Score (CIS) and species for all sites on Batu Caves.

faces (microhabitat i). Their high score is a result of the combination of their threatened status, level of endemism and their being restricted to limestone. Even remnants of the buffer zone (microhabitat c) still also harbour plant diversity.

Table 8. Diversity of microhabitats at Gua Belah on Batu Caves (M – Microhabitats see Table 1).

M	Gua Belah	Total CIS	No. species	No. threatened species	No. endemics	No. restricted to limestone
e	secondary vegetation on steep lower slope above temple	63	21	1	1	1
d	upper steep slope to cave	183	24	3	4	7
f	cave mouth and adjacent wet cliffs	111	10	4	4	6
i	shaded rock scree	217	30	3	7	4
j	wet vertical rocks at cave mouth	105	12	3	4	5
k	inside cave	44	3	1	2	1

Combined Totals: No. species = 100; CIS= 723.

Table 9. Conservation Importance Score (CIS) for sites on Batu Caves.

Site	Total CIS	No. of species	No. threatened species	No. endemics	No. restricted to limestone
10. Gua Belah	723	100	9	13	14
8. Kampung Wira Damai	552	102	6	10	8
7. Temple Cave	329	57	3	5	7
9. Fig Tree Cave	183	25	3	5	7
11.Trek BMX	113	16	2	2	6
5. Kampung Sri Gombak Indah (burnt area)	103	22	1	2	1
6. Kampung Sri Gombak Indah (base)	96	19	0	0	1
1. Taman Sunway Playground	75	17	0	1	1
12. Disused quarry (west side)	60	11	0	2	1
3. Taman Sunway car park (disused quarry)	50	13	1	2	1
2. Nanyang Wall	39	15	0	0	0
1. Disused quarry (south side)	33	28	1	1	1

3. Sites of greatest conservation importance

Sites of greatest conservation importance are recognised by their high total CIS (Table 7). Due to the rugged topography of karst hills, several very different microhabitats can be found at a single site. For example, sites with undisturbed caves, such as Gua Belah, have one of the highest CIS (723) because it covers six different microhabitats (Table 8). Using total CIS as a tool to compare sites, in spite of great variation in area, number of species, level of disturbance etc., it is possible to identify those that are of greatest conservation importance (Table 9).

Sites outstanding for their high total CIS (Table 9, Figure 4, Suppl. material 1: Appendix), include those either where species diversity is particularly high (Site 8 Kampung Wira Damai), the only site on Batu Caves where undisturbed limestone forest persists or where several species of high conservation importance occur, like the summit (Site 9 Fig Tree Cave) or sites that include several different microhabitats, like the sites with caves, such as Site 10 Gua Belah (Table 8) and Site 7 Temple Cave.

Habitat deterioration from anthropogenic activities is the major threat to the biodiversity of Batu Caves and its effect on the flora is brought into focus by comparing their CIS (Table 9). All sites that score less than CIS 100 have been severely disturbed and hardly any or no element of the limestone flora remains. Sites that score between CIS 103–113 are those where, while most of the limestone flora has been eliminated, a

Figure 5. *Epithema parvibracteatum* (Gesneriaceae), endemic to Batu Caves.

Figure 6. The type locality of *Impatiens ridleyi* (Balsaminaceae) in danger.

Figure 7. *Paraboea verticillata* (Gesneriaceae), one of a very few indigenous species that can colonise quarried rock faces.

few species have managed to survive. Sites with a CIS of more than 180 include microhabitats that still retain their diversity and species of conservation importance. However, the deleterious effect of disturbance can be seen by comparing Site 7 (CIS 329) and Site 10 (CIS 723) that are both cave sites with similar microhabitats. Site 7, that houses the Temple Cave, has been heavily disturbed by infrastructure provided to accommodate many visitors compared with Site 10 Gua Belah, which, apart from clearing the limestone forest from the base and lower slopes, is still relatively undisturbed. The only biodiverse microhabitats to survive are the permanently wet vertical walls and stalagmites and the greatly degraded scree, but even so, small populations of the threatened *Begonia phoeniogramma*, *Epithema parvibracteatum* and *Impatiens ridleyi* are greatly reduced and constantly face extermination by new 'beautification' projects.

Discussion

On Batu Caves, 16 microhabitats were identified, each with their own unique assemblage of species, many of which species being restricted to a single microhabitat (Table 7). This emphasises that, for any conservation survey of limestone karst hills, a necessary first step is to identify the various microhabitats and their associated spe-

cies. For the first time, a quantitative method is used that makes it possible to assess the relative conservation important of each microhabitats, irrespective of the number of species recorded (Apppendix). It is important to note that the number of species does not necessarily correlate with the conservation importance of a microhabitat or site although number of species is often used as a criterion in Environmental Impact Assessments (EIA). For example, at Batu Caves, the cave entrance at Gua Belah (Site 10) supports 10 species which together have a CIS of 111, compared with the secondary vegetation growing on the lower slope below Gua Belah that has twice the number of species (21 species), but the CIS is only half (63) that of the cave entrance because most species are widespread weed species with low conservation importance (Table 8).

Amongst the microhabitats on Batu Caves, the three most threatened are (i) the buffer zone of limestone forest; (ii) the lower levels of the steep earth-covered and gullies; and (iii) cave entrances with associated screes. (Other microhabitats with high CIS, like the summit and dolines, are protected by their inaccessibility).

Threatened microhabitats

(a) Buffer zone

For safety reasons (danger to human life of falling rocks or cliff collapse), as well as for preserving the limestone forest, the buffer zone should be at least twice as wide as the highest point of the limestone hill, i.e. for Batu Caves, at least 660 m wide.

At Batu Caves, the original buffer zone of lowland limestone forest has been eliminated as urbanisation and temple infrastructure have pressed to the very base of the vertical cliffs. This tall forest had a closed tree canopy that provided a shaded, humid environment for a variety of shrubs, herbs and ferns. At present, this microhabitat is represented only by a small remnant narrow strip of disturbed forest at Site 11 (Trek BMX), still retains a ground flora of a few threatened, endemic and species restricted to limestone and has a total CIS of 113 (Table 9). The other sites at the base of Batu Caves (Site 2 (Nanyang Wall), Site 4 (Sunway Playground), Site 6 (Kampung Sri Gombak Indah), Site 7 (the Temple Cave), Site 8 (Kampung Wira Damai), Site 10 (Gua Belah) and the three quarry sites) have been cleared and replaced by infrastructure.

Comparison with earlier collections (Kiew et al., in press) indicates that several species collected from the buffer zone at Batu Caves are now probably extinct, such as the extremely rare species, *Polyalthia guabatuensis*, known only from Batu Caves (Turner et al. 2018) and populations of several species, *Sageretia thea* var. *malesiana*, *Sapium insigne* and *Sauropus macranthus* which, in Peninsular Malaysia, were known only from Batu Caves.

The elimination of the buffer zone is a national phenomenon as the great majority of limestone hills are now no longer surrounded by forest. Only about 20–30 of the 445 limestone hills lie within the national or state parks or within forest reserves where they are still surrounded by forest. Liew et al. (2016) were in error reporting that about half the hills had 'good forest cover' and 'most of the forest in the buffer zone was still

in reasonably good condition' because examination of Google Earth maps reveals that this 'forest' is largely oil palm plantation. With no national or state guidelines for the protection of limestone karst hills, whether the surrounding area is used for agriculture or lies within urban areas, forest is cleared to the very foot of the vertical cliffs. This buffer zone of trees is vital and of importance too in protecting the limestone vegetation from fire.

(b) Gullies

Gullies with steep earth-covered slopes are extremely biodiverse in terms of species, for example, Site 8.1 (Kampung Wira Damai) and Site 10.2 (Gua Belah). Gullies are the only microhabitat with a multi-layered limestone forest of tall trees that forms a complete canopy, beneath which shrubs, ferns and herbs can grow in deep shade either rooted in soil or in cracks on outcropping rocks. At Batu Caves, at all sites, the lower levels have been cleared for buildings or for agriculture, mostly for planting fruit trees or have been eliminated by accidental fires. In February 2016, an accidental fire burned for three days and consumed a significant area of Batu Caves (Figure 2). The vegetation on the upper slopes at Site 5 (Kampung Sri Gombak Indah), was nearly eliminated with only a few sizable trees, like *Diospyros wallichii* surviving in spite of its trunk being badly scorched. Pandans with their sappy trunks were particularly susceptible. Six months after the fire, where there was still a soil layer, colonisation was rapid and included species typical of disturbed limestone habitats, such as *Arenga westerhoutii*, *Leucocasia gigantea*, *Musa acuminata* and invasive native species, like the secondary tree, *Macaranga tanarius* and rampant climbers, like *Pterolobium densiflorum*. 'Greening' of the burned area was therefore effected by species with little or no conservation importance. The absence of species of the limestone flora was noticeable. In the last 50 years throughout the Peninsula, fire has become the major threat to limestone forest often the result of clearing lowland forest using fire to establish large palm oil plantations (Davison and Kiew 1990; Aliaa-Athirah et al. 2019; Kiew et al. 2019). The immediate consequence is that cliff faces become covered by rampant climbers that form smothering curtains that can persist for 20 years or more (Kiew et al. 2019) and prevent the regeneration of limestone species.

(c) Caves

Microhabitats associated with caves are often extremely sensitive to disturbance because they depend on the surrounding vegetation to protect their deeply shaded, humid microclimate and prevent them drying out. At Batu Caves, the two large caves, the Temple Cave and Gua Belah, are 'wet' caves, i.e. caves where water regularly drips or runs down the vertical walls of the cave mouths and adjacent cliffs (inside, the caves are dry). The extremely high CIS for caves (CIS 723 for Gua Belah) is primarily due to the variety of microhabitats (Table 8) and to the variety of plant groups, like balsams (*Impatiens*), begonias and Gesneriaceae, like *Epithema*, *Microchirita* and

Monophyllaea species, that flourish in this habitat, many of which are locally endemic and are restricted to limestone. Two Batu Caves endemics, *Epithema parvibracteatum* and *Rhaphidophora burkilliana*, only grow on screes. As early as 1898, Ridley had expressed his concern that building a path up to the Temple Cave would endanger the flora (Wycherley 1972). Since then, a concrete stairway four-flights wide has been constructed and the earth-covered slopes of the former gully have been concreted. In spite of being greatly degraded scree, even small populations of the threatened *Begonia phoeniogramma*, *Epithema parvibracteatum* and *Impatiens ridleyi* still survive at the Temple Cave though their populations are greatly reduced and constantly face extermination by new 'beautification' projects.

Nationally, caves are particularly vulnerable to disturbance whether from guano digging, temple building or, more recently, speleology and eco-recreation. For example, Price (2014) recorded in Peninsular Malaysia at least 70 caves used for Buddhist, Hindu or Taoist temples or monasteries. There is an urgent need for national and state guidelines for the utilisation of caves to avoid irreversible and permanent damage to their biodiversity (Kiew et al. 2020).

Long-term effect of clearing limestone vegetation and its recovery

In spite of widespread disturbance to limestone hills throughout Peninsular Malaysia, no long-term studies have been conducted to assess the ability of the limestone flora to recover after vegetation has been cleared or burned. The area of Batu Caves serves as a case study because, over the years, parts of its vegetation have been eliminated by quarries, encroachment or by fire. While it is too early to assess whether the limestone vegetation will eventually recover from the 2016 fire, examination of degraded sites gives an indication of the ability of the limestone flora to recover (Table 11) from encroachment or mining. While the devastation caused by quarries is plain to see, it is often not obvious to the layman whether the vegetation on a particular limestone hill is pristine or not. Applying CIS provides a method to clearly distinguish pristine limestone vegetation from disturbed/secondary limestone vegetation or from a flora of weeds and alien species (Table 11).

The devastating effect of clearing limestone vegetation is illustrated by the vegetation that now grows on the lower steep earth-covered slope at Site 10.1 Gua Belah (microhabitat e) that was cleared during work on renovating a nearby temple about 10–15 years ago (Table 8). The original primary limestone forest immediately above the cleared site includes 24 species (CIS 183), of which seven have conservation importance (threatened species, endemics and species restricted to limestone), whereas the adjacent cleared area has been invaded by 21 light-demanding weeds and a few fast-growing secondary forest trees, *Macaranga tanarius* and *Homalanthus populneus* (CIS 63). To date the trees still barely reach 2 m tall.

At Site 6 (Kampung Sri Gombak Indah), vegetation was cleared, probably for planting fruit trees (a few lime trees persist at the margin). Now it is dominated by *Macaranga tanarius* that forms a closed tree canopy about 8 m high. That the trees here have large

Table 10. Comparison of the species richness and conservation value amongst the three quarry sites.

Site	Dominant species	Conservation Importance Score (CIS)	No. of species	% weed species	No. primary vegetation species
12. Disused quarry (west side)	*Piper aduncum*	58	11	18	5
1. Disused quarry (Taman Sunway car park)	*Macaranga tanarius*	50	13	38	4
2. Disused quarry (south side)	Herbaceous weeds	33	27	95	0

Table 11. Recovery of the vegetation on degraded sites.

Site	12. Disused quarry (west side)	6. Old clearance (Kampung Sri Gombak Indah)	10a. Cleared 10–15 years ago (Gua Belah)	11. Remnant of buffer zone (Trek BMX)
Dominant tree	*Piper aduncum*	*Macaranga tanarius*	scrub	*Aidia densiflora*
Lower layers	Almost devoid of shrubs and herbs	Shrubs and thick single-species herb layer, ferns	Scrub of shrub and herbaceous weeds	Variety of shrubs, herbs and ferns
Substrate	Rock rubble	Soil, limestone rocks outcropping	Soil, jumble of limestone rocks	Soil, outcropping limestone rocks
Total no. species	11	19	21	16
No. threatened species	0	0	1	2
No. primary species	5 (all saplings)	16	1	12
No. secondary species	4 (saplings or ferns)	3	4	4
No. alien species	2	1	8	0
No. threatened species	0	0	1	2
No. endemic species	2	0	1	2
No. restricted species	1	1	1	6
CIS	58	96	63	113

trunks (about 45 cm diameter) indicates that they are of 'some age'. Unfortunately, it is not known when this site was cleared nor are there data available on growth rates of *M. tanarius*, in spite of it being the most common tree on waste ground in the Kuala Lumpur area. Beneath its canopy, *Wurfbainia biflora*, a ginger that spreads vegetatively by rhizomes, forms a continuous thick carpet and a variety of 15 other ferns, herbs and shrub grow, indicating the beginning of the slow process of recolonisation. However, there is a notable absence of characteristic limestone species, such as species of Annonaceae, climbing aroids and species like *Selaginella*, *Begonia* and *Monophyllaea* that require a deeply shaded humid environment. This accounts for its much lower total CIS (96) for its 19 species compared with the remnant of buffer zone (Site 11) with a CIS of 113 for 16 species. The conclusion is that, even after decades, regeneration has not occurred.

Quarrying, totally and permanently, eliminates the limestone vegetation. At Batu Caves, there has been no attempt to rehabilitate the quarry sites (Tables 9–11) although quarrying stopped about forty years ago in 1982. Only one or two primary limestone species, *Paraboea verticillata* (Figure 7) and *Pandanus penangensis* (though none of the latter is yet of mature size) have been able to become established on the bare cliff faces. They are characteristic of sheer, exposed vertical cliff faces so are, to certain extent, pre-adapted. Otherwise, the quarried cliff faces remain bare and a permanent scar on the landscape.

The flat base of the three quarry sites (Sites 1, 3 and 12) is an artificial habitat. There is no soil layer, the ground instead is covered by small, angular (unweathered)

rubble. The west side quarry (Site 12) has been invaded by the aggressive alien small tree, *Piper aduncum*, that forms a single stand with an open canopy 3–4 m tall. The understorey is almost bare and the few small saplings are scarcely 50 cm tall. At Site 3, a few individuals of the invasive native secondary tree, *Macaranga tanarius*, have become established and, in full sun on the margin, *Pterolobium densiflorum*, an aggressive native climber, smothers the low trees and alien shrubs, like *Lantana camara*. Site 1 is an open area which has been almost invaded by a variety of light-demanding alien weed species devoid of conservation importance. At all sites, there is a notable absence of elements of the limestone flora, which is reflected in their low CIS values (Table 10). There is no indication that these sites will ever recover (Table 11).

In Malaysia, 'rehabilitation' is often the solution to the recovery of biodiversity after being championed by mining companies as a 'mitigating factor'. However, nowhere in the world is there a successful example of rehabilitation that has restored the diverse limestone flora after mining (BirdLife/FFI/IUCN/WWF 2014). This is not unexpected because the majority of limestone species are confined to specific microhabitats, each with specific requirements with regard to substrate, humidity and light etc. With our current lack of knowledge of the autecology of individual limestone species, at best we are able to protect species from extinction by propagating them *ex situ* (Tan 2014).

Indeed, it is instructive to compare regeneration after fire and after quarrying. The burnt site at Batu Caves (Site 5, Table 9) appeared green within about 2–3 years as the area was colonised by fast-growing secondary vegetation, particularly by *Macaranga tanarius*. However, this 'greening' should not be confused with rehabilitation because it did not include species of any conservation importance, apart from those that had escaped the fire.

Lessons from Batu Caves as a case study for assessing plant diversity on limestone hills

In Malaysia and throughout SE Asia, the rapid and ever-increasing demand for cement places karst hills under increasing threat from mining and creates the dilemma of balancing the economic need to exploit limestone hills with conserving their biodiversity and other values, like tourism, eco-recreation, cultural (archaeology and cave temples) and geological values, as well as their value as scenic monuments (Kiew 1997). No country in SE Asia can afford to conserve all limestone hills. There is, therefore, a pressing need for a method to evaluate the conservation value of individual limestone hills to ensure that those of highest conservation importance are identified for protection from mining and other forms of exploitation. The CIS methodology outlined above provides a robust, quantitative and repeatable methodology that produces accurate and reliable quantitative scientific data on the conservation value of individual karsts. It identifies species and microhabitats with the highest conservation importance so that, in cases where hills and their caves are used for recreation or for religious purposes, infrastructure and facilities can be planned so as to avoid unnecessary damage or elimination of species. It also calls attention to the importance of maintaining the original

forested buffer zone when land is being cleared for palm oil plantations or other agricultural or infrastructure purposes.

Batu Caves, as a case study, points the way as to how this might be implemented at the national or regional level. This methodology enables direct comparison of the relative conservation importance of the different hills. This is crucial for implementing conservation strategies for limestone hills in Peninsular Malaysia because a characteristic of the limestone flora is that no individual karst hill harbours more than a fraction of the nation's limestone flora. In Peninsular Malaysia, usually a single limestone hill will harbour no more than about 20%, of the total limestone flora (Kiew 1991) and each limestone hill has its own unique assemblage of species. For example, Batu Caves, the most biodiverse karst in Peninsular Malaysia, is home to 366 species of vascular plants (Kiew et al., in press) out of the estimated 1,216 species listed by Chin (1977).

Differences in the assemblage of species between hills may be ascribed to the different microhabitats present on a single hill (Kiew et al. 2019), the presence of site endemics (Kiew et al. 2017) or phytogeographic distribution patterns of species (Kiew 1991; Rafidah and Kiew 2018). Conservation Importance Scoring (CIS) provides quantitative data that enable the biodiversity of individual hills to be scientifically compared, irrespective of their size, distance from other hills or region in which they occur. For example, adjacent hills do not necessarily harbour the same rare and threatened species (Kiew et al. 2019), nor are large hills automatically more biodiverse or isolated hills have more site endemic species. The comparison of the distribution of site endemic plant species known from less than five limestone hills (Kiew et al. 2017) does not support the view that size of a limestone hill nor its isolation are important indicators of biodiversity, as was suggested by Clements et al. (2008), but instead, diversity of microhabitats is more important (Aliaa-Athirah et al. 2019; Kiew et al. 2019). Mining companies often advocate protecting an adjacent hill on the assumption that the hill will harbour the same biodiversity as the hill to be mined. However, evidence increasingly shows that this is not the case (e.g. Kiew et al. 2014; Aliaa-Athirah et al. 2019; Kiew et al. 2019). As no single limestone hill harbours the entire 'typical limestone flora', instead, a network of hills is needed to conserve maximum diversity. CIS methodology enables karst hills to be ranked and those that harbour outstanding plant diversity, threatened or endemic species can be identified and prioritised for permanent legal protection and not be released for mining.

Important Plants Areas

The three criteria for identifying IPAs are species richness, presence of threatened species and threatened habitats (Anderson 2002). The criteria were revised for tropics to incorporate new elements to be scientifically robust and applicable globally (Darbyshire et al. 2017). Under the Malaysia National Strategy for Plant Conservation, Malaysia is committed to conserve 50% of IPAs (Saw et al. 2009). As limestone areas are recognised nationally as Environmentally Sensitive Areas (ESA Rank 1), limestone

hills automatically qualify as a threatened habitat. On all three criteria, the area of Batu Caves qualifies as an IPA. With 366 species, Batu Caves is more species-rich than any other limestone hill in Peninsular Malaysia (Kiew et al., in press) and it is home to 23 threatened species, of which four are endemic to Batu Caves (Rafidah, in press). However, until today, it still does not have secure legal protection and encroachment continues unabated.

Several state-wide surveys have attempted to rank karst hills by their relative biodiversity importance, based on species lists and identifying rare and threatened species (e.g. for Perak (Malaysian Nature Society 1991); for Kelantan (Davison and Kiew 1990); for Perlis (Kiew 1993)). However, not being quantitative makes comparison of their conservation value between hills difficult when the hills harbour different assemblages of species, different rare and endangered species and different levels of disturbance. Surveying all microhabitats and implementing CIS not only gives weight to threatened species, but also provides a quantitative value for the hill's overall biodiversity and it immediately distinguishes pristine vegetation from disturbed or secondary vegetation or vegetation comprised of alien or weed species. An additional advantage of the CIS over basing comparison mainly on the presence of rare and threatened species is that it also quantifies biodiverse limestone flora that might not include many rare and threatened species. Once a quantitative method, like the CIS method, is implemented, it provides a scientific basis for identifying hills that are IPAs. It is then possible to compare and so rank the 445 limestone hills in Peninsular Malaysia i.e. those of outstanding conservation value that need to be gazetted as Totally Protected Areas to comprehensively protect Peninsular Malaysia's limestone flora. Only those with low biodiversity value or are badly degraded can be considered for exploitation. As a single hill protects only a fraction of the limestone flora, state and national networks of limestone hills need to be identified and protected.

Environmental Impact Assessments (EIA)

In Malaysia, before a mining licence is issued, it is a requirement to carry out a Detailed Environmental Impact Assessment under Environmental Quality (Prescribed Activities) (Environmental Impact Assessment) Order 1987. There are no recommended standard methodologies required. Most frequently, species lists are provided. However, because there is no method to evaluate the conservation importance of species, the lists are often bulked up by listing the scientific names of fruit trees, weeds and other alien species. Indeed, it is not unusual for these lists to include no limestone species at all. The EIAs for mining the Chiku limestone, Kelantan and Gunung Pulai, Kedah, were examples of this practice. That number of species is not a direct indicator of conservation importance of a site is clearly shown at Batu Caves, where disturbed sites can be species-rich with weed species that have no conservation value, whatsoever (compare Site 11 and Site 10.5, for example). Nor is there is any requirement that populations of known narrowly endemic species be located and assessed (Kiew et al. 2019). In a few cases, where results from quadrats and fixed-length transects are included, because of

the rugged terrain, they are usually sited in disturbed vegetation around the flat base of the karst (e.g. G. Kanthan, Perak) and so do not capture the diversity of microhabitats and their species. In fact, results from quadrats and fixed-length transects can be positively misleading in providing species lists of abundant and common weed or secondary species, while entirely missing rare site endemics that occupy narrow microhabitats.

Requiring the implementation of the Conservation Importance Scoring in EIAs would provide a robust methodology that would ensure that species and microhabitats with high CIS are relocated and their populations assessed. Data based on (i) identification and survey of all microhabitats, (ii) search for all known rare and threatened species recorded from the particular hill; and (iii) accurately identified plant species, would provide a sound scientific basis to evaluate the biodiversity importance of an individual karst.

As this plant diversity survey of Batu Caves illustrates, implementation of the CIS, involving survey of all microhabitats for maximum species capture, search for known rare and threatened species and accurate identification of species, provides a robust, quantitative methodology for enabling comparison of individual karst hills at the state or national levels so that those with greatest conservation value can be designated as IPAs and form a network of limestone hills that comprehensively cover the diversity of the limestone flora in Peninsular Malaysia.

Conclusion

The multiple values of karst limestone hills, as illustrated by Batu Caves, result in stakeholders with disparate interests, varying from commercial (mining and eco-recreation), to cultural (temple caves and tourism), to historic (archaeological deposits), to natural heritage (landscape and geological features) and to biodiversity (flora and fauna and the cave ecosystem) (Kiew 1997; Kiew et al. 2020). There is, therefore, a need to balance these disparate values so that they do not result in degradation or permanent damage to karst limestone hills.

In spite of massive changes in the surroundings of Batu Caves in the last 130 years when the surrounding lowland rainforest was cleared, first for plantations and then by urban encroachment, Batu Caves still retains much of its limestone flora, including most of its rare and threatened species. Results of the Rapid Biodiversity Assessment and the expedition illustrated the importance of identifying the many and varied microhabitats that exist on Batu Caves that contribute to its species richness and that, if microhabitats remain intact, significant biodiversity and threatened species persist.

At Batu Caves, continuing encroachment has almost eliminated the buffer zone. Indeed, four species that formally grew in this forested buffer zone are now considered to be probably extinct (Rafidah, in press). In addition, without the buffer zone, the hill is more vulnerable to fire and, in 2016, a major fire eliminated a large area of the limestone vegetation. Nationally, the loss of the buffer zone of limestone forest (twice as wide as the highest point of the hill) is a major threat, not only because it safeguards

the flora, but as a barrier against fire. In the last fifty years, fire has become a major threat to limestone vegetation. In Peninsular Malaysia, only 20–30 of the 445 hills lie in national or state parks or forest reserves and are still surrounded by forest.

The quarries established at Batu Caves, the first more than a hundred years ago, are by today's standards small and impacted only small parts of the hill. Nationally, however, quarrying is now on a massive scale often consuming entire hills, for example, quarrying of Bukit Sagu and Bukit Tenggek, Pahang, that resulted in *Paraboea bakeri* becoming extinct in the wild. It is still maintained in tissue culture in the Forest Research Institute Malaysia (Tan 2014). The Batu Caves survey also illustrates that, even after forty years since the last quarry closed, the limestone flora has not recovered. The blasted rock faces remain bare and the flat land at the base is almost exclusively colonised by weeds and alien species.

With this accelerating encroachment and exploitation, not only at Batu Caves, but throughout Malaysia and the region, there is an urgent need to identify those hills, that have high biodiversity, are still pristine and harbour threatened and site endemic species. It is crucial for national and state guidelines for the utilisation of karst limestone hills and their caves to be implemented to avoid irreversible and permanent damage and extinction of species (Kiew et al. 2020).

Conservation management is only possible when the distribution of species and their microhabitats is understood. The novel CIS method is here shown to be a rapid, effective and quantitative method that enables the conservation value of species, microhabitats and limestone hills to be assessed quantitatively. It enables IPAs to be identified and will enable ranking of hills so that a network of limestone hills can be identified for inclusion in the legal gazette at both state and national levels. Batu Caves qualifies on all criteria as an Important Plant Area and needs to be legally protected and its status strictly enforced to prevent further deterioration. The CIS method should also be the recommended methodology for EIAs. One restriction of the CIS methodology is that it does not provide quantitative data on the rarity of species and thus does not provide information on the status of the population and its long-term sustainability of a particular species. Carrying out assessments of population size on karst limestone is particularly difficult because of the extremely rugged topography. However, the CIS does pinpoint those species with the highest CIS that are known from a single hill and the microhabitat in which they grow that can be the focus of future detailed studies of their population size, autecology and, in cases where they are threatened, *ex situ* cultivation.

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Supplementary material 1

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